METHOD FOR INCREASING THE STRENGTH OF A VOLUME OF SOIL, PARTICULARLY FOR CONTAINING AND SUPPORTING EXCAVATION FACES

Technical field

The present invention relates to a method for increasing the strength of a volume of soil, particularly for containing and supporting excavation faces. More particularly, the method according to the present invention allows to contain and support in a vertical position, or in a position that is slightly inclined with respect to the vertical, an excavation face or otherwise a mass of soil, improving resistance to all the various stresses of a portion (or band) of said soil that is interposed between the excavated volume and the volume of natural soil left in place.

Background art

More generally, the method according to the invention can be used to constitute a portion (or band) of improved and reinforced soil within a volume of soil, for example in order to stabilize or increase the stability safety of a slope, of a vault of a tunnel or of any other situation in which a volume of soil, due to the force of gravity or to other forces, tends to undergo deformation, generating failure surfaces internally.

In order to better understand the subject of the present invention, definitions of technical terms from the specific field, that will be used in the description of the invention, are given hereinafter. For the technical terms that are not defined hereinafter, reference is made to the technical literature of the field.

The expression "excavation face" designates the vertical surface, or surface inclined with respect to the vertical, that is formed as a consequence of an excavation between the volume of soil left in place and the volume that was occupied by the soil removed with the excavation means. The inclination of said surface tends to follow a natural lie.

The expression "natural lie" of the excavation face designates the lie

that an excavation face constituted by natural soil naturally assumes once the soil adjacent to it is removed. This lie, which normally has an inclination between 20° and 50° with respect to a horizontal plane, depends exclusively on the shear strength of the volume of soil left in place adjacent to the excavation.

The expression "thrust wedge" designates the (generally wedge-shaped) volume of soil comprised between the surface of the excavation face and the natural lie.

The expression "substantially" means "to a substantial degree".

Figure 1 illustrates the above definitions.

The expression "bulkhead" designates any structure that is intended to retain a volume of soil that would otherwise assume, due to its weight and to other external forces, the shape of its own natural lie.

The expression "shear strength" or "shear stress resistance" of a volume of soil designates the resistance opposed by a soil to the shear stresses that act along any surface that intersects it. It is constituted, according to the well-known Mohr-Coulomb law, by two mutually independent components: the component due to cohesion and the component due to internal friction.

The formula that determines shear strength τ is as follows:

$$\tau = c + \sigma \cdot \mathrm{tg}\,\phi$$

where:

c = soil cohesion;

σ = applied tension;

ϕ = internal friction angle of the soil.

For the sake of simplicity, the two components c and $\sigma \cdot \mathrm{tg}\,\phi$ that determine shear strength are termed respectively "shear strength due to cohesion" and "shear strength due to internal friction".

Soils are generally divided into two types:

-- granular soils;

-- cohesive soils.

Both of these categories of soil have a shear strength that allows them to form a natural lie when lateral support is no longer provided and they are therefore excavated. The inclination of said natural lie, if no auxiliary support elements intervene, depends as mentioned exclusively on the average shear strength of the soil.

Granular soils, i.e., coarse-grain soils (pebbles, gravels, sands) have a shear strength that depends exclusively on internal friction, i.e., on the confinement pressure to which the granules are subjected and on the internal friction angle. These soils in fact have no cohesion.

The internal friction angle is a characteristic that is typical of the material and depends mainly on the geometry of the granules and on their arrangement within the matrix; the confinement pressure to which the granules are subjected depends exclusively on the load that affects them. For an equal internal friction angle, shear strength increases as the confinement pressure applied to the granules increases.

Cohesive soils, i.e., soils having a fine particle size (silt, clays) have a shear strength that depends mainly and almost entirely on cohesion. Their behavior is in fact different in non-drained conditions and in drained conditions. To clarify this aspect, one should bear in mind that drained or non-drained conditions depend exclusively on the presence of water within the matrix, i.e., between the granules. Since granule size in cohesive soils is very small, drained conditions occur a very long time after excavation, since all the water contained between the grains has to flow out. Drained behavior of cohesive soils associates a shear strength that depends on cohesion and on internal friction force. Non-drained conditions instead occur both during and directly after excavation and associate a shear strength that depends exclusively on cohesion.

The natural lie of an excavated soil increases in steepness with

respect to the horizontal as the shear strength of said soil increases.

In many kinds of cohesive and granular soil, even with a high shear strength, the natural lie that occurs once excavation has been completed does not coincide with a vertical surface; i.e., after excavation the natural lie does not remain stably at an inclination proximate to 90° with respect to the horizontal plane.

In order to safely maintain an excavation face in a vertical position or in a position that is slightly inclined with respect to the vertical it is necessary to intervene by erecting suitable bulkheads.

In densely populated areas, where it is necessary to perform excavations in order to build underground spaces adjacent to existing buildings with surface foundations, or where it is otherwise necessary to provide an excavation with a highly inclined face despite the absence of nearby buildings, it is necessary to act preventively in order to increase the inclination of the natural lie of the soil until it coincides with the chosen excavation face, which can even be vertical.

Figure 2 illustrates what has just been described.

In a different field, the problem of instability of a slope that is not necessarily steeply inclined may occur. Landslides (as shown in Figure 3) are in fact generally linked to the insufficient strength of the layers of soil that are arranged proximate to the deep slip surface. The volume of soil that lies above said surface, due to its own weight, in fact tends to break the deep soil, inducing horizontal displacements that are dangerous for buildings arranged at the surface. In these situations it is necessary to improve the strength at least of the layers of soil that are crossed by the slip surface and to connect the unstable volume to the stable volume by installing supporting reinforcements.

In other cases, the problem of instability of a vault in a tunnel may occur (Figure 4). Performing an excavation, albeit one having a circular cross-section, can induce in the volume of soil that lies above the vault

strong tangential tensions that can cause the collapse of the overlying soil (sinkhole). In these situations it is essential to act prior to excavation work by consolidating the volume above the vault.

Various systems are known which are suitable to support an excavation face, even in the presence of water, while performing an excavation whose inclination with respect to the horizontal plane is greater than the natural lie.

In general, these are systems that support the excavation face by virtue of the horizontal reaction offered by a fence of piles, generally made of concrete with a steel core, which are arranged side by side at the face to be excavated. The lower end of the piles ends deeper, i.e. at a greater depth than the excavation bottom level, while the upper end of the piles ends within a stiffening strip generally made of concrete. This method is generally known as the "Berlin wall" or "micropile wall" and can be completed by building ties that are connected thereto and are inserted with various inclinations and lengths in the volume of soil behind the face.

Among the other known systems for supporting the excavation face, mention is made of concrete bulkheads that contrast the thrust wedge in a manner that is similar to Berlin walls but are mainly constituted by continuous bulkheads of reinforced concrete of variable thickness that are built directly into the soil before performing the excavation and are optionally completed by anchoring ties.

Both of these technologies, in addition to being highly invasive, since they require the use of very large machines, require very long times and entail very high costs.

Among other known technologies for supporting the excavation face, mention is made of the system by means of which the excavations are strutted by means of buttresses directly after producing them. This method, sometimes very risky and in any case scarcely applied, does not allow to use completely the excavated volume, since said volume is occupied by the

supporting structures.

Moreover, a method is known by means of which the excavation faces are supported by steel sheet piles that are driven well below the maximum excavation depth, before performing said excavation, by means of vibration systems. This method sometimes cannot be applied, since the machines required for the installation are large and the vibrations produced during driving can damage nearby buildings.

Another known method for supporting the excavation face is constituted by the use of nails of different lengths, which are driven into the ground at right angles to the face directly after providing an excavation or a portion of an excavation. Said nails are adapted to increase the shear strength of the soil behind the face. However, in the time interval between execution of the excavation and nail driving, an unexpected instability may occur which can lead to the collapse of the face or of part of said face. In general, in any case, this method, known as "soil nailing", entails the use of large machines and high installation costs.

Another known method consists of injecting cement mixes into the soil proximate to the face to be provided, in order to increase the shear strength of the soil. This method, known as "jet grouting", requires high injection pressures (300-600 bar) for correct execution. These pressures may cause migration of the injected cement mixture into volumes of soil that are distant from the intended ones, causing considerable damage to nearby buildings. Moreover, this technology can be applied only to granular soil. These characteristics, together with high installation costs, limit considerably the application of this method in the urban environment.

Disclosure of the Invention

The aim of the present invention is to provide a method for increasing the resistance to all the various stresses of a portion (or band) of soil, particularly for containing and supporting excavation faces, that is capable of solving the problems noted above with reference to known types of

method.

Within this aim, an object of the invention is to provide a method that allows to increase satisfactorily the resistance to all the various stresses of a portion (or band) of soil with distinctly lower costs than those required by known types of method.

Another object of the invention is to provide a method that can be performed in a short time and with compact equipment.

Another object of the invention is to provide a method that can be performed in absolute safety even in the immediate vicinity of dwellings and even if the space available is limited.

This aim and these and other objects that will become better apparent hereinafter are achieved by a method for increasing the strength of a volume of soil, particularly for containing and supporting excavation faces, characterized in that it comprises at least one reinforcement step that comprises the following steps:

- a step for preparing receptacles for a reinforcement structure, in which a plurality of mutually spaced reinforcement holes are formed, said holes being arranged substantially vertically or inclined with respect to a vertical direction in the volume of soil to be strengthened;
- a step for inserting the reinforcement structure, during which reinforcement elements are inserted in said reinforcement holes;
- a step for locking the reinforcement structure, during which a synthetic locking substance that expands by chemical reaction is injected into said reinforcement holes, said substance being adapted to bond said reinforcement elements with the surrounding soil.

<u>Brief description of the drawings</u>

Further characteristics and advantages of the invention will become better apparent from the description of a preferred but not exclusive embodiment of the method according to the invention, illustrated by way of non-limiting example in the accompanying drawings, wherein:

Figure 1 is a schematic view of a volume of soil affected by an excavation;

Figure 2 is a schematic view of the execution of an excavation near a building;

Figure 3 is a schematic view of a very steep slope;

Figure 4 is a schematic view of the danger of sinkhole forming in the soil above the vault of an excavation for building a tunnel;

Figures 5 to 11 are schematic views of the sequence of execution of the method according to the invention in a volume of soil, shown in a cross-section taken along a vertical plane;

Figure 12 is a top plan view of the situation of Figure 6;

Figure 13 is an enlarged-scale view of a detail of Figure 6;

Figure 14 is a top plan view of the situation of Figure 10;

Figure 15 is an enlarged-scale view of a detail of Figure 10.

Ways of carrying out the invention

With reference to Figures 5 to 15, the method according to the invention, in the preferred embodiment illustrated in said figures, comprises a step for consolidating the volume of soil whose resistance to all the various stresses is to be increased.

This consolidation step comprises a drilling step, during which a plurality of mutually spaced injection holes 1, which are substantially vertical or inclined with respect to a vertical direction, are produced in the volume of soil 2 to be strengthened proximate to the excavation face 10 to be performed later or proximate to the exposed face of the volume of soil 2 to be strengthened (Figure 5). The exposed face can be constituted for example by the face of an excavation that has already been performed or by the slope of a hillside.

The injection holes 1 are produced at a distance from the excavation face 10 to be produced or from the exposed face of the volume of soil affected by the work that is preferably substantially but for little variations

comprised between 0.10 m and 2.00 m.

The distance between two contiguous injection holes 1 is preferably substantially comprised between 0.20 m and 2 m.

The diameter of the injection holes 1 is preferably substantially comprised between 12 mm and 180 mm.

Depending on the work requirements, the injection holes 1 may be arranged, in plan view, in rows that are substantially parallel to the excavation face 10 or to the exposed face of the volume of soil being treated, with a distance between two contiguous rows of injection holes 1 that is substantially comprised between 0.10 m and 2.00 m.

The length of the injection holes 1 can vary according to the conditions of the soil and according to the operating requirements. Depending on said requirements, the injection holes 1 may have such a length as to cross, as shown, the natural lie 11 or may be shorter.

An injection step is subsequently performed (Figures 6, 12 and 13); in said step, a synthetic consolidation substance 3 that expands by chemical reaction and is suitable to compress and compact the surrounding soil (Figure 7) as a consequence of its expansion is injected into the injection holes 1.

The synthetic substance 3 is injected into the injection holes 1 by means of injection tubes 4 that are inserted in the injection holes 1 before starting the injection and are gradually extracted from said injection holes 1 during injection.

The injection tubes 4 preferably have a diameter substantially comprised between 6 mm and 30 mm.

The injection tubes 4 can be made of copper, steel, PVC, or other material, and their external surface is conveniently treated with, or made of, a lubricating substance so as to facilitate as much as possible the extraction of the injection tubes 4 from the injection holes 1.

The synthetic substance 3 that is injected into the injection holes 1, as

a consequence of the expansion due to chemical reaction, preferably has a potential increase in volume that is substantially comprised between 2 and 30 times, preferably between 5 and 30 times, its initial volume, i.e., the volume of said synthetic substance prior to expansion. The expression "potential expansion" is used to reference the expansion that the synthetic substance 3 would undergo if its expansion occurred freely in air. The actual expansion of the synthetic substance 3 is inversely proportional to the resistance opposed by the soil to this expansion when the substance is injected into the injection holes 1.

The maximum expansion pressure generated by the synthetic substance 3 during expansion is higher than the tension in the volume of soil affected by the injection holes 1, so as to obtain, by virtue of the expansion of the synthetic substance 3, a good compaction of the soil proximate to the injection holes 1, saturating any voids and compacting the granules of the matrix of the soil. The maximum expansion pressure of the synthetic substance 3 depends on the composition of the synthetic substance 3 and increases as the resistance opposed by the soil to this expansion increases. The maximum expansion pressure of the synthetic substance 3 in fully confined conditions is conveniently comprised between 200 KPa and 10,000 KPa and is preferably higher than 500 KPa.

The expansion of the synthetic substance 3 produces a compaction of the soil that surrounds the injection holes 1, improving its strength in general and its resistance to compression, shear and torsional stresses in particular.

The synthetic substance 3 is a substance that is composed of at least two components that are mixed in an appropriate device and are pumped into the injection tubes 4, generally with a pressure comprised between 5 and 30 bar.

The synthetic substance 3 preferably has a reaction time, understood as the time interval between the moment when the components are mixed

and the moment when expansion begins, that is substantially comprised between 2 and 80 seconds, preferably comprised between 2 and 15 seconds.

The reaction time of the synthetic substance 3 is such as to allow said substance to flow correctly through the injection tubes 4 and at the same time prevent the substance, prior to expansion, from being dispersed excessively in the soil, so as to achieve maximum soil compaction in the chosen regions, i.e., in the soil located in the immediate vicinity of the injection holes 1.

Also for the same purpose, the viscosity of the synthetic substance 3 prior to the chemical expansion reaction is preferably comprised between 100 mPa·s and 700 mPa·s at the temperature of 25°.

Furthermore, the viscosity of the synthetic substance 3 changes from said value to a value that tends to infinity in a time interval of 5 to 20 seconds starting from when the chemical expansion reaction begins.

The synthetic substance 3 is preferably constituted by a closed-cell polyurethane foam.

Said foam is preferably constituted by an MDI isocyanate and by a mixture of polyols.

Merely by way of example, the MDI isocyanate can be constituted by the product URESTYL 10, manufactured by the Dutch company Resina Chemie, and the mixture of polyols comprises a polyether polyol and/or a polyester polyol, a catalyst, and water, like the product Resinol AL 1409 manufactured by the same company.

The mixing of these two components produces an expanding polyurethane foam whose density, at the end of expansion in air, i.e., without any confinement, is equal to approximately 30 Kg/m^3 and varies according to the resistance opposed to the expansion to which it is subjected, up to a maximum of 1200 Kg/m^3. Generally, the density of the synthetic substance 3, as a consequence of its injection in the injection holes 1, after expansion, varies from 100 Kg/m^3 to 400 Kg/m^3.

Advantageously, the dispensing of the synthetic substance 3 and/or the extraction rate of the injection tubes 4 from the corresponding injection holes 1 are varied according to the stratigraphic characteristics of the soil being treated, which are analyzed beforehand, in order to dispense larger quantities of synthetic substance 3 at the weaker layers of soil and smaller quantities of synthetic substance 3 at the stronger layers of soil. In this manner, the synthetic substance 3, as it exits from the lower end of the injection tube 4, is deposited within the surrounding soil in a quantity that is inversely proportional to the initial strength of the soil, unless there are different specific requirements.

The variation of the quantity of synthetic substance 3 dispensed in the various layers of soil can be achieved by pumping into the injection tube 4 a constant flow-rate of synthetic substance 3 and by varying according to the stratigraphic characteristics of the soil being treated the extraction rate of the injection tube 4 from the corresponding injection hole 1, or by maintaining a constant rate of extraction of the injection tube 4 from the corresponding injection hole 1 and varying the flow-rate of synthetic substance 3 that is pumped into the injection tube 4. In order to achieve this result in an optimum manner, it is possible to use modern injection machines that allow to inject, at the same injection pressure, constant or adjustable flow-rates of material regardless of the soil resistance conditions, such as for example the SR-200-GE model manufactured by the United States Gusmer corporation.

The synthetic substance 3, once injected and hardened, preferably has a tensile strength substantially comprised between 0.75 MPa and 5.50 MPa, a compressive strength substantially comprised between 0.68 MPa and 8.78 MPa, a flexural strength substantially comprised between 0.95 MPa and 6.00 MPa, and a shear strength substantially comprised between 0.34 MPa and 4.39 MPa, respectively at the densities of 100 Kg/m^3 and 400 Kg/m^3.

Furthermore, the modulus of elasticity of the synthetic substance 3

after its expansion and hardening is on the same order of magnitude as the modulus of elasticity of the soil into which it is injected, so as to ensure complete cooperation between the two materials in any condition of deformation that occurs on site, i.e., with a value preferably lower than 500 MPa.

After the consolidation step, the method according to the invention comprises a reinforcement step, which comprises a step for preparing receptacles for a reinforcement structure. This step of preparation of receptacles for a reinforcement structure consists in providing, in the soil on which the previous consolidation step has been performed, i.e., proximate to the injection holes 1, multiple or a plurality of reinforcement holes 5 that are mutually spaced and are substantially vertically elongated or inclined with respect to a vertical direction in the volume of soil 2 whose resistance to all the various stresses is to be increased proximate to the excavation face 10 to be produced subsequently or proximate to the exposed face of the volume of soil whose resistance to all the various stresses is to be increased (Figure 8).

The reinforcement holes 5 are produced at a distance from the excavation face 10 to be performed or from the exposed face of the volume of soil affected by the treatment that is preferably substantially comprised between 0.10 m and 2.00 m.

The distance between two contiguous reinforcement holes 5 is preferably comprised substantially between 0.20 m and 2.00 m.

The diameter of the reinforcement holes 5 is preferably substantially comprised between 12 mm and 180 mm.

Depending on the requirements of the treatment, the reinforcement holes 5 can be arranged, in plan view, along rows that are substantially parallel to the excavation face 10 or to the exposed face of the treated volume of soil, with a distance between two contiguous rows of reinforcement holes 5 that is substantially comprised between 0.10 m and 2.00 m.

Reinforcement elements are then inserted in the reinforcement holes 5 thus provided; said reinforcement elements are preferably constituted, for each reinforcement hole 5, by a bar that has a solid cross-section or by a tubular element 6 that preferably has openings 6a on its lateral surface, or the like (Figure 9).

If the reinforcement element is constituted by a bar that has a solid cross-section, its diameter is smaller than the diameter of the corresponding reinforcement hole 5, so as to allow a certain play between the bar and the side walls of the corresponding reinforcement hole 5.

If instead the reinforcement element is constituted by a tubular element 6, its diameter may also be equal or only slightly smaller than that of the corresponding reinforcement hole, for reasons that will become better apparent hereinafter.

The reinforcement elements may have a length that is equal to, or greater than, the reinforcement holes 5. The length of the reinforcement elements and of the reinforcement holes 5 is in any case such as to cross the natural lie 11 or the deep slip surface of the volume of soil whose resistance to the various stresses is to be increased.

Preferably, the reinforcement elements and/or the reinforcement holes 5 have a length that allows them to penetrate for at least 0.5 m into the soil that lies below the natural lie 11 or the deep slip surface of the volume of soil whose resistance to the various stresses is to be increased and in any case always beyond the level of the future bottom of the excavation.

The reinforcement holes 5, and accordingly the reinforcement elements, can be inclined with respect to the vertical on a parallel plane or on a vertical plane that is perpendicular to the excavation face, or can be inclined with respect to the vertical both on a parallel plane and on a vertical plane that is perpendicular to the excavation face, preferably with an inclination that is directed toward the volume of soil to be strengthened.

For a viewer located in front of the future excavation face, the

distribution of the reinforcement holes 5 and of the corresponding reinforcement elements, from his (front) viewpoint, may appear vertical, inclined with respect to the vertical to the left or to the right, or provided with a "crossed" configuration: some holes and corresponding reinforcement elements arranged with a rightward inclination with respect to the vertical and some holes and corresponding reinforcement elements arranged with a leftward inclination with respect to the vertical.

For a viewer located above with respect to the future excavation face with the horizontal face line, the distribution of the holes and corresponding reinforcement elements may appear, from his viewpoint (from above), vertical with respect to the face, inclined with respect to the excavation face toward the volume of soil to be supported, inclined to the left or to the right on the plane of the excavation face, or "crossed": some holes and corresponding reinforcement elements are arranged at a rightward angle with respect to the vertical and some holes and the corresponding reinforcement elements are arranged with a leftward inclination with respect to the vertical, or with an inclination determined by the combination of the positions described above.

For a viewer arranged to the side of the future excavation face, the distribution of the holes and of the corresponding reinforcement elements, from his (lateral) viewpoint, may appear to be vertical or inclined with respect to the vertical toward the soil to be supported.

The reinforcement elements have a tensile strength exceeding 5 MPa and a shear strength exceeding 0.3 MPa. The tubular elements 6 preferably have an outside diameter substantially comprised between 12 mm and 180 mm and an inside diameter preferably comprised between 8 mm and 150 mm.

The lateral openings 6a formed in the lateral surface of the tubular elements 6 preferably occupy at least 30% of the total lateral surface of the tubular elements 6.

The reinforcement elements, be they bars having a solid cross-section or tubular elements, may be made of various materials, such as for example fiberglass-reinforced plastic, steel, metal alloys, synthetic materials or other materials.

After the arrangement of the reinforcement elements in the reinforcement holes 5, a step for locking the reinforcement elements in the corresponding reinforcement holes 5 is performed by injecting a synthetic locking substance 7 that expands by chemical reaction and is injected into the reinforcement holes 5 laterally to the reinforcement elements. If the reinforcement elements are constituted by tubular elements 6 with openings 6a, the synthetic substance 7 is preferably injected into the tubular elements 6 so that it exits from the lateral openings 6a and also penetrates into the contiguous soil (Figures 10, 11, 14 and 15).

The synthetic substance 7 is injected by means of injection tubes 8 that are similar to the injection tubes 4 described earlier and are inserted in the reinforcement holes 5 laterally or internally with respect to the reinforcement elements before beginning the injection and are gradually extracted from the reinforcement holes 5 during the injection of the synthetic substance 7.

The synthetic substance 7 used in this step has technical characteristics that differ from those of the synthetic substance 3 used in the previous consolidation step.

More particularly, the synthetic substance 7 that is injected into the reinforcement holes 5, as a consequence of expansion by chemical reaction, preferably has a potential increase in volume substantially comprised between 1 and 5 times its initial volume, i.e., the volume of said synthetic substance prior to expansion. The actual expansion of the synthetic substance 7 is inversely proportional to the resistance opposed by the soil to this expansion when the substance is injected into the reinforcement holes 5.

The maximum expansion pressure generated by the synthetic

substance 7 during expansion is preferably lower than the possible breaking strength of the soil that has undergone the previous consolidation step and is located around the reinforcement hole 5. The maximum expansion pressure of the synthetic substance 7 depends on the composition of the synthetic substance 7 and increases as the resistance opposed to this expansion by the soil increases. The maximum expansion pressure of the synthetic substance 7 in fully confined conditions is conveniently comprised between 20 KPa and 200 KPa.

For an optimum outcome of the method according to the invention, the maximum expansion pressure of the synthetic substance 7 must greatly decrease with a minimal increase in volume of said substance as a consequence of the chemical reaction, so as to ensure, if completely confined within a volume of soil that was previously subjected to the consolidation step or is already inherently strong enough, a great reduction in expansion pressure as a consequence of a minimal degree of expansion, preferably even less than 5%, and therefore before the surrounding treated soil breaks. In this manner, complete bonding of the injected synthetic substance 7 with the surrounding soil is ensured, consequently avoiding local breaking, which might compromise the continuity of the system. In case of any breakage of the soil, the synthetic substance itself may re-bond it locally.

The synthetic substance 7, prior to the chemical expansion reaction, preferably has a viscosity comprised between 100 mPa·s and 500 mPa·s at 25°, so as to allow uniform flow out from the openings 6a of the tubular element 6 and/or allow complete surrounding of the reinforcement element in general, so as to bond the system constituted by the soil, the expanding material and the reinforcement element.

Furthermore, the viscosity of the synthetic substance 7 passes from said value to a value that tends to infinity in a time interval of 10 to 80 seconds starting from the beginning of the chemical expansion reaction.

The synthetic substance 7 is also a substance composed of at least two components that are mixed in a suitable apparatus and are pumped into the injection tubes 8, generally with a pressure comprised between 2 and 30 bar.

The synthetic substance 7 preferably has a reaction time, understood as the time interval that elapses between the time when the components are mixed and the time when expansion begins, that is substantially comprised between 2 and 80 seconds.

The synthetic substance 7 is preferably also constituted by a closed-cell polyurethane foam.

Said foam is preferably constituted by an MDI isocyanate and by a mixture of polyols.

Merely by way of example, the MDI isocyanate may be constituted by the product URESTYL 10, produced by the Dutch company Resina Chemie, while the mixture of polyols comprises a polyether polyol and/or a polyester polyol, a catalyst and water, like the product Resinol AL 1287 by the same company.

The mixing of these two components produces an expanding polyurethane foam whose density, at the end of its expansion in air, i.e., without any confinement, is at least equal to 200 Kg/m^3 and varies according to the resistance to expansion to which it is subjected. Generally, the density of the synthetic substance 7 as a consequence of its injection into the reinforcement holes 5 after expansion varies from 400 Kg/m^3 to 800 Kg/m^3.

This density, which is characteristic of the synthetic substance 7, allows it to reach very high stress resistance values and therefore to effectively contribute to the extraction resistance that the reinforcement elements must have in order to contribute to supporting the thrust wedge.

The synthetic substance 7 in fact is meant to ensure the anchoring of the reinforcement elements to the soil that it passes through.

In order to better clarify the importance of the synthetic substance 7,

one should consider by way of example a reinforcement structure constituted by a bar with an outside diameter of 30 mm that is inserted in the volume of stable soil that lies below the thrust wedge for at least 1.00 m.

The lateral outer surface S_L meant to cooperate with the soil in order to ensure anchoring is equal to:

$$S_L = \pi \cdot D \cdot L = 942 \text{ cm}^2$$

The shear strength of the synthetic substance, considering an expansion equal to 5 times its initial volume, and therefore with a density of 200 Kg/m^3, is equal to 14.00 Kg/cm^2 (approximately 1.4 MPa).

Assuming a safety factor $F_S = 3$ that takes into account the fact that the extraction resistance generated by the reinforcement structure affects the system constituted by the soil and the synthetic substance and not only the synthetic substance, the following design shear strength is assumed:

$$\tau = 14.00 / 3 = 4.70 \text{ Kg/cm}^2 \text{ (approximately 0.47 MPa)}$$

This strength value leads to a reaction to extraction offered by the reinforcement that is equal to:

$$R_S = \tau \cdot S_L = 4430 \text{ kg (43.458 N)}$$

If instead one uses, in order to lock the reinforcement structure, a synthetic substance that has a maximum degree of expansion equal to 30 times (for example of the type used during the consolidation step), after injection, in extreme conditions, one would have a synthetic substance with a final density of 30 kg/m^3. This density would have provided a final shear strength of the synthetic substance equal to 2.1 kg/cm^2 (approximately 0.21 MPa), which in view of the safety factor $F_S = 3$ for the reasons described earlier, provides a design shear strength equal to:

$$\tau = 2.10 / 3 = 0.70 \text{ Kg/cm}^2 \text{ (approximately 0.07 MPa)}$$

This shear strength value would lead to an extraction reaction for the reinforcement structure of:

$$R_S = \tau \cdot S_L = 660 \text{ kg (6.474 N)}$$

The described example shows that the use of a high-density synthetic

substance to lock the reinforcement structure entails a considerable difference in terms of resistance to extraction of the reinforcement structure..

The synthetic substance 7, once injected and hardened, preferably has a tensile strength substantially comprised between 5.60 MPa and 17.80 MPa, a compressive strength substantially comprised between 8.78 MPa and 34.42 MPa, a flexural strength substantially comprised between 7.18 MPa and 11.98 MPa, and a shear strength substantially comprised between 4.40 MPa and 17.20 MPa, respectively at the densities of 400 Kg/m^3 and 800 Kg/m^3.

After the reinforcement step, it is possible to proceed with the anchoring of the upper ends of the reinforcement elements. Said anchoring can be performed in various manners according to the requirements. If there are buildings adjacent to the excavation face, for example, the upper ends of the reinforcement elements that protrude from the reinforcement holes 5 may be fixed to the foundation structure of the building by installing bars, connecting beams or other means, or can be embedded directly onto the foundation structure by using hydraulic binders or by means of the expanding synthetic substance itself if the reinforcement holes 5 have been produced by passing through the foundation structure of the building. If there are no buildings adjacent to the excavation face, the upper end of the reinforcement elements can be anchored with the aid of ties to be driven into the volume of stable soil.

However, anchoring of the upper end of the reinforcement elements is not always necessary.

If the strength and composition characteristics of the soil in the natural state whose resistance to all the various stresses is to be increased are such as to allow the injected synthetic substance, once the chemical expansion reaction is completed, to have a high final density (approximately 250-400 Kg/m^3), such as to ensure high resistances to shear stresses (and therefore high adhesion to the reinforcement structure); the method

according to the invention can be performed in a simplified form, or second embodiment, by avoiding the preventive consolidation step and performing only the reinforcement step. In this case, the synthetic substance injected into the reinforcement holes 5 is chosen so as to achieve simultaneously a consolidation of the soil that surrounds the reinforcement holes 5 and an adequate locking of the reinforcement elements in the reinforcement holes 5.

In this case, the synthetic substance that is injected into the reinforcement holes 5, as a consequence of its expansion by chemical reaction, preferably has a potential increase in volume substantially comprised between 2 and 30 times its initial volume, i.e., the volume of said synthetic substance prior to expansion. The actual expansion of the synthetic substance is inversely proportional to the resistance opposed by the soil to this expansion when the synthetic substance is injected into the reinforcement holes 5.

The maximum expansion pressure generated by the synthetic substance used in this simplified version of the method according to the invention, during expansion, exceeds the tension in the volume of soil affected by the reinforcement holes, so as to achieve, by virtue of the expansion of the synthetic substance, also a compaction of the soil proximate to the reinforcement holes 5. More particularly, the expansion of the synthetic substance, in this case, also has a compaction effect on the granules of the matrix of the soil, increasing its compressive strength, shear strength and torsional strength. The maximum expansion pressure of the synthetic substance depends on the composition of the synthetic substance and increases as the resistance opposed by the soil to this expansion increases. The maximum expansion pressure of the synthetic substance, in fully confined conditions, is preferably comprised between 20 KPa and 10,000 KPa.

In the simplified embodiment of the method according to the

invention, owing to the fact that the strength and composition characteristics of the soil in the natural state to be strengthened are such as to allow the injected synthetic substance, once the chemical expansion reaction has ended, to have a high final density (generally comprised between 250 Kg/m^3 and 400 Kg/m^3), such as to ensure high shear strengths (and therefore high resistance to extraction of the reinforcement elements), the synthetic substance that is used may also be the consolidating synthetic substance that can be used in the consolidation step described with reference to the first embodiment of the method according to the invention.

In the presence of a high but not sufficient degree of strength of the soil, the method can be performed in a third embodiment, which is intermediate with respect to the two previously described embodiments and according to which the injection step and the reinforcement step are performed substantially simultaneously. More particularly, in said third embodiment, provision of the reinforcement holes and installation of the reinforcement elements are performed as preliminary operations; then, preferably halfway along the center distance between the individual reinforcement holes, injection holes are provided, in a manner similar to what has been described with reference to the first embodiment of the method.

This third embodiment of the method according to the invention allows to provide holes with a procedure that is easier and quicker, since the soil crossed for perforation has not yet been compressed and consolidated. One then proceeds with the injections of synthetic expanding substance into the injection holes and finally with the injections for locking the reinforcement structure in the soil, optionally using the same expanding synthetic substance that is injected into the injection holes. Said synthetic expanding substance is preferably constituted by the synthetic consolidation substance described earlier with reference to the consolidation step in the first embodiment of the method according to the invention. In this third

embodiment of the method, the soil, which is already strong to begin with, is compacted considerably with the injections of synthetic expanding substance into the injection holes, and therefore when the synthetic expanding substance is injected into the reinforcement holes in order to lock the reinforcement elements, it has a strength that is sufficient to ensure that the expanding synthetic substance reaches a density comprised between 250 Kg/m^3 and 400 Kg/m^3 and therefore offers an adequate shear strength (and therefore an adequate resistance to the extraction of the reinforcement elements). In this case also, the injection for fixing the reinforcement structure also contributes to a further compaction and aggregation of the surrounding soil. Furthermore, since the reinforcement holes and the reinforcement elements are at a certain distance from the injection holes and therefore the soil that is present proximate to the reinforcement holes is not constituted by soil aggregated with resin, the injections into the reinforcement holes optionally performed with expanding synthetic substance having a high expansion force do not entail the risk of breaking the soil aggregated with resin that is at a certain distance from the reinforcement holes, but provides a strong compaction and a new aggregation of the soil that surrounds said reinforcement holes.

The choice of the embodiment of the method according to the invention to be adopted depends on the initial conditions of the soil and on the loads that bear on it, as well as on the end result that is to be achieved.

For example, where it is necessary to considerably increase the resistance of a soil to all the various stresses, either because its initial strength is poor or because the height of the excavation face and the loads to be withstood are high and such as to increase the various compressive stresses, shear stresses and torsional stresses and generate tensile and flexural stresses, it is preferable to use the method in the first embodiment, which is more complete and which, despite having greater burdens in terms of consumption of material and in terms of ~~execution~~ times, allows to

considerably increase the strength of the soil and therefore the safety of the excavation.

Optionally, in the second and third embodiments of the method according to the invention also, the delivery of expanding synthetic substance and/or the rate at which the injection tubes are extracted from the corresponding reinforcement holes or injection holes may be changed according to the stratigraphic characteristics of the soil being treated and previously investigated, so as to deliver larger quantities of synthetic expanding substance at the weaker layers of soil and smaller quantities of synthetic substance at the stronger layers of soil, in a manner similar to what has already been described with reference to the first embodiment of the method.

In these two last embodiments also, after the reinforcement step it is optionally possible to anchor the upper end of the reinforcement elements in the manners that have already been described.

The synthetic substances that are used in the method according to the invention do not undergo alterations during expansion or after expansion and hardening as a consequence of the presence of water, even if it is acid and/or rich in sulfates, carbonates or salts in general, in the treated soil. Moreover, said substances do not pollute the soil subjected to the treatment or the underlying aquifer.

In practice, the method according to the invention, by insertion, in a suitable position, into a portion (or band) of soil, of reinforcement elements that are bonded, by means of injections of expanding synthetic substance, to the soil that constitutes said portion (or band), gives the volume of soil affected by the method a tensile strength, and therefore a flexural strength, increasing the resistance of said portion (or band) to all the various stresses. This increase in resistance is also assisted by the consolidation of the soil produced by the expansion of the synthetic substance that is used to lock the reinforcement elements and optionally by the expansion of an expanding

synthetic substance injected into the soil in holes that are different from the holes that accommodate the reinforcement elements. Said consolidation in fact increases the compressive strength, shear strength and torsional strength of said natural soil that constitutes the treated portion (or band).

It will be seen that, the method according to the invention provides from scratch a bulkhead for the excavation face by using a portion (or band) of said soil, optionally suitably improved in terms of strength with respect to compressive stresses, shear stresses and torsional stresses by means of injections of a synthetic expanding substance, in which a reinforcement structure is locked in a suitable position in order to not only improve the strength of the assembly constituted by the soil and the reinforcement structure with respect to compressive stresses, shear stresses and torsional stresses, but also to provide a tensile strength, and therefore a flexural strength, that otherwise would not be possible with the soil alone, even if it were consolidated.

Moreover, with the present invention a bulkhead inside the soil is therefore built preferably prior to the excavation inside said soil; said bulkhead is constituted by a composite material formed by soil, synthetic substance and reinforcement structure, and is adapted to withstand all possible types of stress, including tensile and flexural stresses.

The method according to the invention allows to constitute a soil bulkhead made of composite material behind the excavation face, using as a first element the soil itself, which is left in place and improved with the injection of expanding synthetic substances, and the reinforcement structure as a second but fundamental element.

The soil alone, despite being improved with injections of expanding synthetic substance, is in fact a material whose tensile strength and consequently flexural strength is considered zero for calculation purposes and therefore for safety purposes: the presence of the slightest discontinuity within its structure can completely eliminate its overall strength. The overall

strength of the structure is in fact the result of the combination of all the resistances to the various simple stresses; the lack of just one of the various resistances to the stresses that act, such as for example tensile strength (a fundamental component also for flexural strength), can completely invalidate the supporting function entrusted to the structure.

The assembly constituted by the soil, the expanding synthetic substance and the reinforcement structure therefore has a composite behavior, entirely similar to that of reinforced concrete, dictated by the characteristics of its individual elements: the consolidated soil, the expanding synthetic substance and the reinforcement structure. In particular, the deformations that the bulkhead will undergo will depend directly on the deformability of the elements that constitute it.

Furthermore, the presence of the reinforcement structure adjacent to the excavation face or the exposed face of the soil is an effective barrier against slippage that might occur locally. Distribution at regular intervals of the reinforcement elements adjacent to the excavation face or to the exposed face of the soil in fact produces in the soil located to the rear a horizontal reaction that prevents the occurrence of said local instability phenomena.

The result of the method according to the invention can be easily assessed by comparing penetrometer tests performed in the thrust wedge after execution of the method with penetrometer tests performed prior to performing the process.

In particular, if the method according to the invention is used to increase resistance of a portion (or band) of a volume of soil to all the various stresses before performing an excavation, it is possible to perform the excavation in absolute safety, avoiding the execution of even small portions of excavation without predicting their outcome.

It is known from the literature that the shear strength and the simple compressive strength of a soil are directly proportional to the resistance opposed by said soil to the advancement of a penetrometer. Therefore, by

comparing the results of penetrometer tests performed in the portion (or band) of the volume of soil that constitutes the bulkhead prior to performing the method according to the invention with the results of penetrometer tests performed in the same portion (or band) of volume of soil that constitutes the bulkhead after performing the method according to the invention, it is possible to determine, by means of simple calculations, the increase in compressive strength and shear strength produced by the expansion of the synthetic substances used. By adding the contribution in terms of compressive strength and shear strength provided by the injections of synthetic substances and the contribution in terms of compressive strength and shear strength provided by the reinforcement structure, whose mechanical strength characteristics are known, as well as the new tensile strengths provided by said reinforcement structure thoroughly bonded with the containing soil, it is possible to know exactly, before performing the excavation, the value of the resistance of the soil to the various stresses. In particular, the flexural strength provided by the new bulkhead constituted by the soil, the expanding synthetic substance and the reinforcement structure can be obtained by considering the pair constituted by the compressive strength of the consolidated soil and the tensile strength of the reinforcement structure adequately positioned in the volume of soil.

In practice it has been found that the method according to the invention fully achieves the intended aim and objects, since it can be performed with distinctly shorter times and lower costs than known types of method and can be performed with compact equipment and even in the immediate vicinity of dwellings and with limited space available.

In particular, if the method according to the invention is performed in preparation for performing an excavation, it is necessary to wait only one day at the most after the treatment before performing the excavation. Moreover, said method:

- allows to provide the entire support of the excavation face before the

excavation operations begin, so as to avoid creating overlaps between the excavation work and the face supporting work;

- ensures maximum safety during excavation by providing safety factors in compliance with currently applicable statutory provisions;
- furthermore ensures maximum safety during treatment since it does not require high working pressures to inject the expanding substances or intense forces in order to install the reinforcement structures.

Another advantage is constituted by the fact that the expansion of the synthetic substances used preventively induces in the soil to be excavated a state of tension that exceeds geostatic tension. This "prestressing" characteristic allows greater detensioning of the soil during excavation operations before causing large displacements or deformations.

The method according to the invention is particularly suitable for application in an urban environment, where the risk of causing damage to nearby dwellings is high, the spaces available for building yard equipment are limited, it is necessary to cause minimum inconvenience to the nearby buildings, and the time available to perform the excavation is generally very limited.

The method thus conceived is susceptible of numerous modifications and variations, all of which are within the scope of the appended claims; all the details may furthermore be replaced with other technically equivalent elements.

The disclosures in Italian Patent Application No. MI2003A002154 from which this application claims priority are incorporated herein by reference.